Digitization of Chaotic Signal for Reliable Communication in Non-Ideal Channels

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ABSTRACT
A new method of chaotic communication system based on digitization of the chaotic signal is proposed. The digitally encoded chaotic signal is transmitted through a practical channel and recovered at the receiver. Simulation results show that despite being errors in the received bit sequence, the observer is able to synchronise and recover message signal with high accuracy provided bit error rate is < 10^{-4}. The proposed method is compatible with the existing digital communication system and hence could be implemented in real scenario with no or little modification in the existing infrastructure.
Keywords: digitization of chaotic signals, Lorenz, observer.

1. INTRODUCTION

Since it was shown that chaotic synchronization is possible [1, 2], research interest in chaotic signals for achieving security in communication systems [3-8] or spread spectrum applications [9] have been growing. Chaotic signals have number of interesting properties including broadband spectrum, sensitivity to the initial conditions and parametric mismatch, and aperiodicity. A number of different techniques have been proposed where chaotic signals are used for achieving secure communication links. These techniques deal mainly with two major issues, mixing and transmission, and synchronization between transmitter and receiver. Methods of masking [1], parametric modulation [10], and inclusion methods [11] have been proposed for analogue systems, while the chaotic shift keying (CSK) [12] has been proposed for digital communications. Variations of these methods have also been reported to overcome the shortcomings of these methods [5, 13]. The drive response principle, generalized synchronization, phase synchronization, observer based synchronization, impulsive synchronization, the extended Kalman filtering have been proposed for synchronization [1, 5, 8, 14]. Various attacks for assessing_the security of these methods have also been proposed for masking [15], parametric modulation [16], inclusion [16], CSK [16], and other modified methods [13]. For a complete survey refer to [8, 17].

All the new schemes proposed so far for chaotic communications mainly deal with the security, synchronization or parametric mismatches issues. However, very little work has been reported on the performance of the system when operated in a real channel with noise, attenuation, fading, multipath and dispersion. In fact, some of the schemes proposed may not work satisfactorily at all when real channel is used. In [18] it has been shown that signal recovery is not possible at signal-to-noise ratio (SNR) of 35 dB or higher. In [19, 20] channel equalisation and noise combating techniques have been reported but the main focus has been on the spread spectrum application or the chaotic maps rather than the continuous-time chaotic systems. Currently, the majority of the chaotic communication methods proposed do not complement with the existing digital communication schemes but requires to be implemented differently. Thus, leading to parallel development of error correction, equalisation, and dispersion compensation schemes. Therefore, it is logical and a step forward move if future development in chaotic communication systems can be built on the existing technologies.

In this paper, we propose a novel method where the chaotic signals are first digitized and converted into binary data sequences. These binary sequences are transmitted using the conventional digital communication links. At the receiving end, the digital sequence is regenerated using existing technology where the error correction, equalisation and dispersion compensation can readily be applied. The recovered chaotic signal can be used for chaotic synchronization and extraction of the actual hidden message signal. In this method, it is shown that message recovery is possible with a high degree of accuracy at moderate SNR of 14 dB even when the bit error rate (BER) is very high. The SNR required to recover message can further be reduced by implanting the error correction codes and digital signal processing tools which are already well established in digital communication. The security issues are not taken into consideration in this study and a simple chaotic masking is used to demonstrate the concept of digitization.

2. DIGITIZATION OF CHAOTIC SIGNAL

The schematic block diagram of the proposed system is shown in the Fig. 1. Assuming a band limited chaotic signal and provided the sampling rate is higher than the Nyquist rate the continuous chaotic signal $y(t)$ can be represented in discrete format Y_i. $y(t)$ is converted into a digital format with uniform sampling before being digitally encoded. Assuming the discrete memoryless source (DMS), the simplest encoding scheme of fixed length code word of n-bits per sample is used for representing the binary digits. Different coding techniques (i.e.

pulse code modulation (PCM), differential PCM (DPCM), adaptive PCM, delta modulation) could be applied to reduce the quantization error and hence improve the performance. In this paper, PCM with uniform quantization level is used. Investigating the systems performance using other coding techniques could be a subject of further study. Simple baseband modulation technique of on-off keying (OOK) with 100% duty cycle is used for the digital transmission.

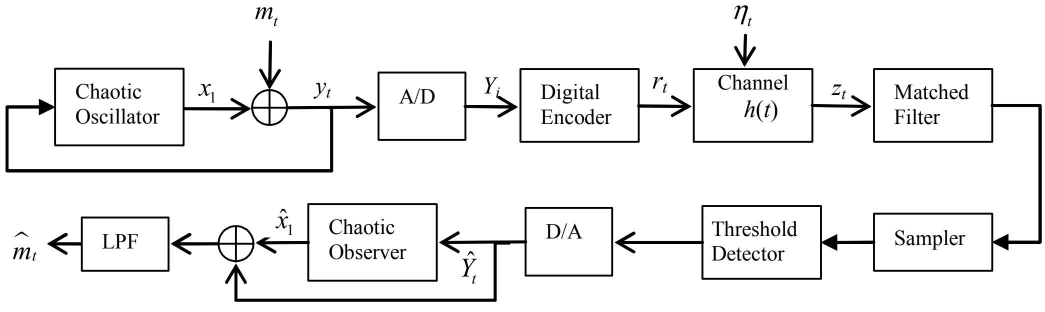


Fig. 1. Block diagram of proposed chaotic communication system using digitization.

The channel $h(t)$ is assumed to be additive white Gaussian (AWG). At the receiver a matched filter followed by a sampler and a threshold detector are used to regenerated the binary sequence $\hat{Y}_i$. The binary sequence is converted back into analogue chaotic signal using D/A. A chaotic observer is used to recover the original message signal.

The robust observer is implemented where it can synchronize with the chaotic oscillator at transmitter even though it is driven by a quantized chaotic signal. Let us define the chaotic oscillator in transmitter as follow:

$$\begin{aligned} \dot{x} &= \mathbf{A}x + \mathbf{B}g(y,t) \\ y &= \mathbf{C}x \end{aligned} \tag{1}$$

where $x \in R^n$, $y \in R$ and g is a smooth function. **A**, **B** and **C** are matrix of appropriate dimensions. In our design, we are using Lorenz equation as chaotic oscillator at transmitter side where state x_1 is taken as output y where message m_t is masked.

Assuming that the pair ($\boldsymbol{C}$,$\boldsymbol{A}$) is rank observable, the observer for the system (1) can be defined as:

$$\dot{\hat{x}} = \mathbf{A}\hat{x} + \mathbf{B}\,g(y,t) + \mathbf{K}_p\left(y - \mathbf{C}\hat{x}\right) \tag{2}$$

where the gain $\mathbf{K}_p$ is chosen such that the matrix $\left(\mathbf{A} - \mathbf{K}_p\mathbf{C}\right)$ is stable.

By setting $\dot{e} = \hat{x} - x$, the error dynamics is given by:

$$\dot{e} = \left(\mathbf{A} - \mathbf{K}_p\mathbf{C}\right)e \tag{3}$$

Since $\left(\mathbf{A} - \mathbf{K}_p\mathbf{C}\right)$ is stable, the error $\dot{e}$ asymptotically converges to zero ensuring synchronization.

Converting the chaos signal into a digital format has the advantages of being able to transmit it through existing communications links wired or wireless (radio or optical) taking advantage of the existing infrastructure. Problems including noise, multipath induced distortion and dispersion, and fading can readily be dealt with in the digital domain. For example, it is rather complicated and challenging to design equalizing filters for chaotic communications since it has a broad spectrum. However, with digitization of chaotic signal this is no longer a major problem. One key advantage of the proposed system is the perfect reconstruction of the chaotic signal at the receiver having been propagated through a real channel. The metric for comparing the performance and measuring the reliability of digital communication system is the bit error rate (BER). In this paper, we study the performance of the communication system for different BER. Once the minimum BER require for message recovery is set, the error control coding, (e.g. convolutional, turbo and a low parity density codes) can be used to improve the BER performance and hence increase reliability [21].

It is to be noted that in the analysis of chaotic system, researchers generally tend to consider the channel to be noise-free and non-dispersive. However, physical channels are always noisy and may be dispersive. Nevertheless, with the digitization concept as proposed in this paper, the dispersion can simply be compensated by means of equalizers including like linear equalizer, decision feedback equalizers and the more recently reported wavelet and artificial neural network (ANN) based equalizer [22].

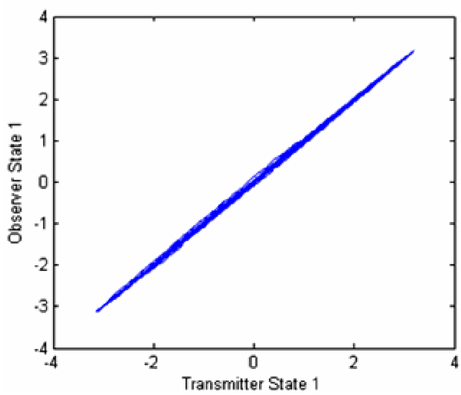
In the next section, we will verify the proposed method by presenting some simulation results.

3. SIMULATION RESULTS AND DISCUSSION

Simulation of the proposed chaotic communication system using digitization is done using the Matlab/Simulink. We have used the popular Lorenz system [1] as a chaotic oscillator. The masking method adopted includes the message of $m = \sin(\omega t)$ with $\omega = 1$ rad/sec and the resulting output signal is sampled and quantized using an A/D converter. The quantization resolution n is 6. The digital sequence in OOK format is transmitted through the non-ideal channel. The SNR is varied in order to achieve BER of different order. To accurately estimate the message signal, the performance of the system is examined for over a range of BER and a threshold BER is determined.

Figure 2 illustrates the synchronization between the observed state $\hat{x}_1$ and the transmitter state x_1. The 45º line indicates perfect synchronization illustrating robustness of the observer synchronization. Now let us see how accurately the message is recovered for a given BER. Figure 3 depicts time waveforms for transmitted and recovered message signal m at a BER of 10^{-6}. To reduce the effect of quantization error an 8th order low-pass Butterworth filter with a cut off frequency of 2 rads/sec is employed to extract the message signal.

For a reliable digital communication link the optimum BER is considered to be 10^{-6}. We can see in Fig. 3 that the perfect recovery of message is possible at BER of 10^{-6}. Figure 4 shows the recovered message time waveform at BER of 10^{-3}, 10^{-4} and 10^{-6}. The proposed scheme is still able to extract the message signal with reasonable quality at BER of 10^{-4}. However, there is some distortion for higher values of BER (i.e. 10^{-3}). These results demonstrate the potential of this scheme for BER of $< 10^{-4}$ over noisy channel condition. The proposed system can readily be implemented using existing commercial components. To further increase the performance of the system, quantization error can be reduced using DPCM scheme, or other advanced source coding, which can be subject of further study.



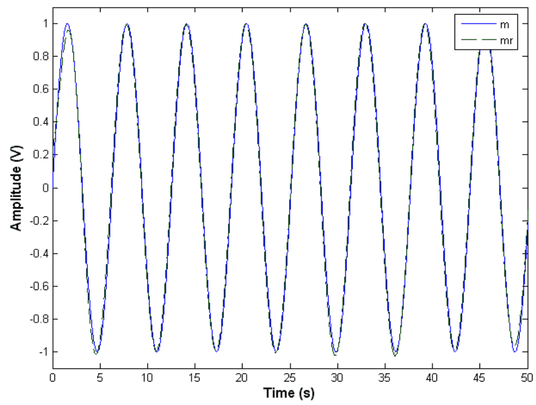


Fig. 2. Synchronization between states used for masking. Fig. 3. Transmitted and recovered message at BER 10^{-6}.

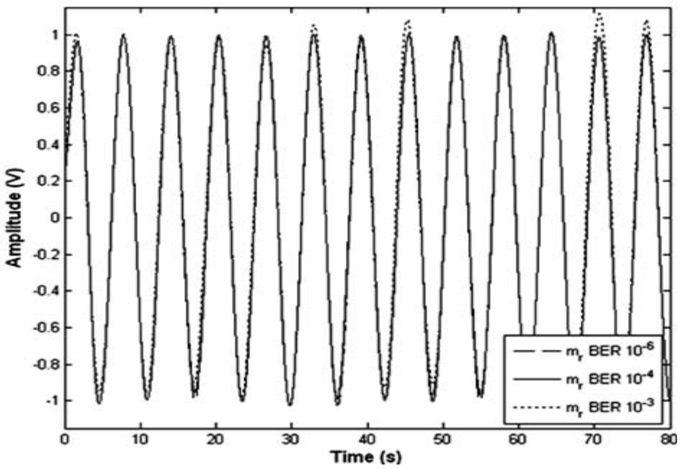


Fig. 4. Recovered message at different BER.

4. CONCLUSIONS

A new method of chaotic communication system based on digitization was proposed and the results were obtained by means of simulation. Although the chaotic signal was transmitted as digital bit sequence, it was possible to recover the signal using the conventional digital communication technique. Chaotic synchronization was obtained even though the observer was driven by the quantized chaotic signal and reliable recovery of the message was demonstrated at optimum BER of 10^{-6}. BER was increased to 10^{-4}, message recovery was still possible at 10^{-4} but at BER > 10^{-4} there were some distortion on the recovered signal. The channel considered in the study was a typical AWGN channel. In physical channel, maximum likelihood sequence detector, wavelet based equalizer, ANN based equalizer can be used to mitigate the effect of intersymbol interference due to dispersion.

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